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Competitive subluminal LIV limits from ultra-high energy astrophysics

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In this contribution, we introduce subluminal Lorentz invariance violation (LIV) in the propagation of ultra-high energy photons. The energy threshold and the mean free path for the pair production considering LIV are calculated. The influence of the models for the sources of ultra-high energy cosmic rays in the flux of GZK photons is discussed. The resulting fluxes for several sources models and LIV scenarios are obtained and compared to the upper limits on the photon flux from the Pierre Auger Observatory. Updated limits on the LIV coefficient of the order of $\delta_{\gamma,0} \gtrsim -10^{-20}$, $\delta_{\gamma,1} \gtrsim -10^{-38}$ eV and $\delta_{\gamma,2} \gtrsim -10^{-56}$ eV^2 are imposed for the reference case. The possibility of testing superluminal LIV effects is also discussed.

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1. Introduction

Lorentz invariance violation (LIV) has been proposed by several high energy models as a possible departure from relativity [1]. It has been widely tested in different experimental approaches, and restrictive limits have been imposed [2]. The effect is expected to be suppressed by the energy and, thus, astroparticles could be suitable probes for LIV, being the most energetic known particles in the Universe [3].

LIV could lead to new effects such as the energy-dependent speed of light, vacuum Cherenkov, photon decay, and changes in the kinematics of interactions. These effects would leave imprints in astrophysical data and, consequently, could be used to look for LIV signals and to impose limits on LIV. For a review of the most updated LIV limits from astrophysics see Ref. [2].

In this work, we discuss the results obtained by Lang *et al.* [4] by searching subluminal LIV signals with ultra-high energy (UHE, $E > 10^{18}$ eV) astroparticles. The propagation of UHE photons was modified by LIV and is shown in Section 2. In particular, the case of GZK photons was treated. Firstly, the importance of the assumptions about the UHECR sources in the flux of GZK photons is discussed in section 3.1. Then, the flux of GZK photons on Earth for each source assumption and LIV scenario is obtained in Section 3.2 and limits on the LIV coefficient are imposed in Section 4. Finally, the possibility of testing superluminal is considered in Section 5, and the conclusions are presented in Section 6.

2. Pair production including LIV

A phenomenological approach for LIV such as the Coleman & Glashow formalism [5] is proposed. LIV is introduced as a perturbative correction to particle energy dispersion relation:

$$E_a^2 - p_a^2 = m_a^2 + \sum_n \delta_{a,n} E_a^{n+2}, \tag{2.1}$$

where E, p and m denote, respectively, the energy, momentum, and mass of the particle a and $\delta_{a,n}$ is the LIV coefficient, which modulates the LIV effect. In phenomenological approaches, it is usual to consider LIV only for one particle species and look separately for each approximation order, n. $\delta_{a,n}$ is set as a free parameter, which can be either positive or negative, to be constrained or measured by the analysis. In this work only subluminal LIV in the photon sector for the first three leading orders are considered, leading to a modified photon dispersion relation:

$$E_\gamma^2 - p_\gamma^2 = m_\gamma^2 + \delta_{\gamma,n} E_\gamma^{n+2}, \tag{2.2}$$

with $\delta_{\gamma,0}$, $\delta_{\gamma,1}$, $\delta_{\gamma,2} < 0$.

Propagating UHE photons interact with the photon background via pair production ($\gamma + \gamma_{CB} \rightarrow e^- + e^+$), which attenuates the flux of UHE photons expected on Earth [6]. Changing the photon dispersion relation changes the energy threshold of the pair production:

$$\varepsilon_{th}^{\mathrm{LIV}} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n} E_\gamma^{n+1}}{4}, \tag{2.3}$$

where $\varepsilon_{th}^{\mathrm{LIV}}$ is the energy threshold considering LIV, m_e is the electron mass, and K is the inelasticity.

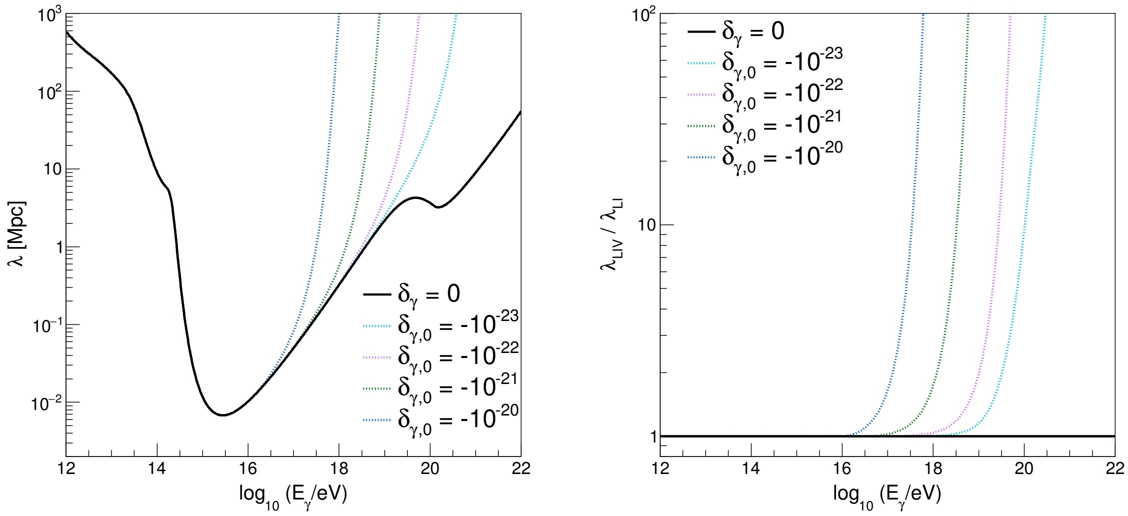

Figure 1: Mean free path for the pair production as a function of the photon energy. The black continuous line represents the LI scenario while the colored dashed lines represent scenarios with different LIV coefficients. The left panel shows the absolute mean free path, while the right panels shows the fraction of the LIV to the LI mean free path.

Therefore, subluminal LIV leads to an increase in the energy threshold of the interaction. This becomes more tangible when looking at the mean free path of the interaction, given by:

$$\lambda(E_\gamma) = \int_{-1}^{1} d(\cos\theta)\frac{1-\cos\theta}{2}\int_{\varepsilon_{th}^{\mathrm{LIV}}}^{\infty} d\varepsilon n_{CB}(\varepsilon,z)\sigma(E_\gamma,\varepsilon,z), \tag{2.4}$$

where σ is the cross-section on the interaction [7] and n_{CB} is the density of background photons, which is dominated by the extra-galactic background light (EBL) for $E_\gamma < 10^{14.5}$ eV, the cosmic background microwave radiation (CMB) for $10^{14.5}$ eV $< E_\gamma < 10^{19}$ eV and the radio background (RB) for $E_\gamma > 10^{19}$ eV. The Gilmore model [8] is considered for the EBL and the Gervasi model with a cutoff at 1 MHz [9] is used for the RB.

Figure 1 shows the mean free path as a function of the energy for several LIV coefficients for $n = 0$. Similar results are found for $n = 1$ and $n = 2$. The main LIV effect is an increase in the mean free path above given energy, which depends on the LIV coefficient. It is, thus, expected that under a LIV assumption, UHE photons would travel farther and, consequently, an enhanced flux of UHE photons on Earth would be expected.

3. Flux of GZK photons

Propagating UHECR interacts with the photon background and produce pions. The neutral pions shortly decay, generating EeV photons, called GZK photons. In this work, we obtain the expected flux of GZK photons considering LIV. The mean free path presented in Section 2 was implemented in the Monte Carlo code *CRPropa3/EleCa* [10]. The propagation of UHECR and resulting GZK photons was simulated considering sources up to 9500 Mpc and the spectrum of UHECR was normalized to the spectrum measured by the Pierre Auger Observatory [3] at $E = 10^{18.75}$ eV.

3.1 Influence of the UHECR source in the flux of GZK photons

The flux of GZK photons strongly depends on the assumptions about the sources of UHECRs. To understand this influence, four different models for the injected spectra of cosmic rays at the sources (C_i) and five different models for the redshift evolution of the sources (R_i) were considered.

The injection models, C_i consider a power law injection with a maximum rigidity cutoff and 5 different masses injected (H, He, N, Si and Fe). Each model can be described by the spectral index, Γ, rigidity cutoff, R_{cut} and the masses fractions (fH, fHe, fN, fSi and fFe) as shown in Table 1.

Model	Γ	$\log_{10}(R_{cut}/\mathrm{V})$	fH	fHe	fN	fSi	fFe	Reference
C_1	1	18.699	0.7692	0.1538	0.0461	0.0231	0.00759	[11]
C_2	1	18.5	0	0	0	1	0	[12]
C_3	1.25	18.5	0.365	0.309	0.121	0.1066	0.098	[12, 13]
C_4	2.7	∞	1	0	0	0	0	[14]

Table 1: Models considered for the injection spectra of UHECR.

The models for the evolution of the sources with redshift R_i follow star formation distributions and GRB rates and are given by:

- R_1: sources uniformly distributed in a comoving volume;
- R_2 : Proportional to $(1+z)^{3.4}$, for $z<1$, to $(1+z)^{-0.26}$ for $1 \leq z < 4$ and to $(1+z)^{-7.8}$ for $z \geq 4$ [15];
- R_3 : Proportional to $(1+z)^{3.4}$, for $z<1$, to $(1+z)^{-0.3}$ for $1 \leq z < 4$ and to $(1+z)^{-3.5}$ for $z \geq 4$ [16];
- R_4 : Proportional to $(1+8z)/[1+(z/3)^{1.3}]$ [17];
- R_5 : Proportional to $(1+11z)/[1+(z/3)^{0.5}]$ [17];

Figure 2 shows the comparison of the expected flux for each of the models. Different model assumptions can lead to several orders of magnitude of difference in the resulting flux for the injected spectra and up to 500% difference for the redshift evolution. The assumptions about the UHECR sources, thus, play a critical role in the resulting flux of GZK photons and, consequently, should not be neglected in such studies.

3.2 Integral flux considering LIV

The two limiting cases, i.e., $\delta_\gamma = 0$ (LI) and $\delta_\gamma \to -\infty$ (maximum LIV, in which no interaction is allowed at all energies) were considered as well as several intermediate LIV coefficients for $n =$ 0, 1 and 2. We have obtained the resulting flux on GZK photons for each LIV assumption and combination of models C_iR_j and compared them to the upper limits on the photon flux imposed by the Pierre Auger Observatory [18]. Figure 3 shows the resulting fluxes for the reference model C_3R_5.

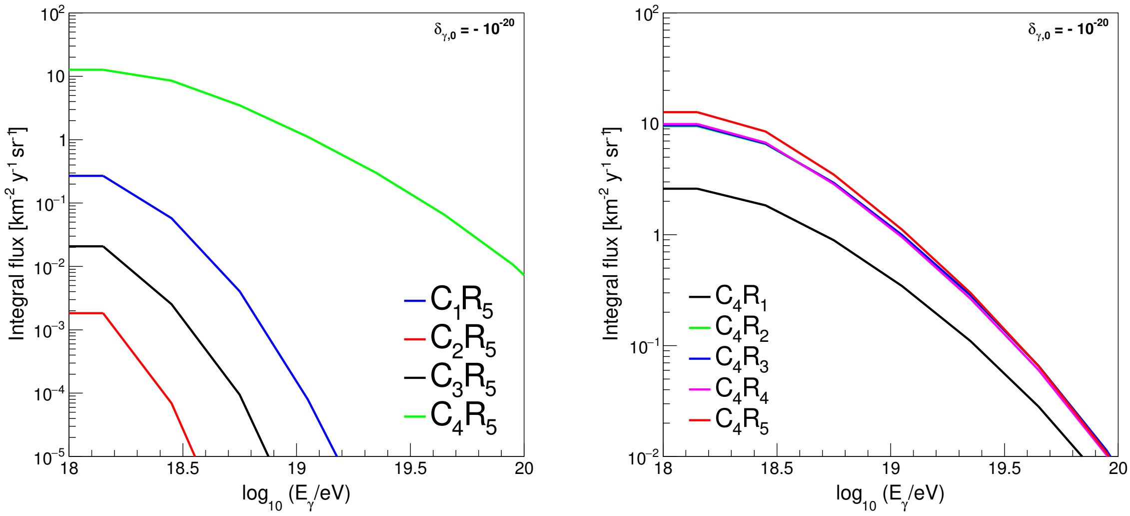

Figure 2: Integral flux of GZK photons as a function of the energy. The left panel shows different models for the injection spectra, C_i, for a fixed redshift evolution model, R_5, while the right panel shows different redshift evolution models, R_i, for a fixed injection spectra model, C_4. A LIV scenario with $\delta_{\gamma,0} = -10^{-20}$ is considered for all cases.

4. Limits on the LIV coefficients

As expected, when LIV is considered, the flux is enhanced. For some of the cases, the flux becomes larger than the limits from Auger and, therefore, limits on the LIV coefficient are imposed. Figure 4 compares the limits obtained for the reference case in this work with previous subluminal LIV from astrophysics. The limits are several orders of magnitude more restrictive than the ones imposed using TeV gamma-rays [20, 21, 22, 23]. The comparison with these limits, however, is not straight-forward since different photon energies, systematics and astrophysical assumptions are used. The limits from ref. [19] use a similar technique as the one used in this work. However, as shown in Table 2, this work updates the assumption about the sources and the data used.

	Composition	Photon flux limits	UHECR spectrum normalization
Lang *et al.*	Mixed [12, 13]	Pierre Auger 2015 and 2017 [18]	Pierre Auger 2017 [3]
Galaverni *et al.*	Pure proton	Pierre Auger 2007	AGASA 2008

Table 2: Comparison of the assumptions made and data used by Lang *et al.* 2018 and previous work using similar technique and astrophysical results.

5. Superluminal LIV

We present the energy threshold and mean free path for the pair production considering superluminal LIV effects ($\delta_\gamma > 0$) instead of subluminal in Figure 5. The effect is opposite to the one obtained for the subluminal case, i.e., there is a decrease in the energy threshold and a resulting decrease in the mean free path. It is, thus, expected a weaker flux of GZK photons and, therefore,

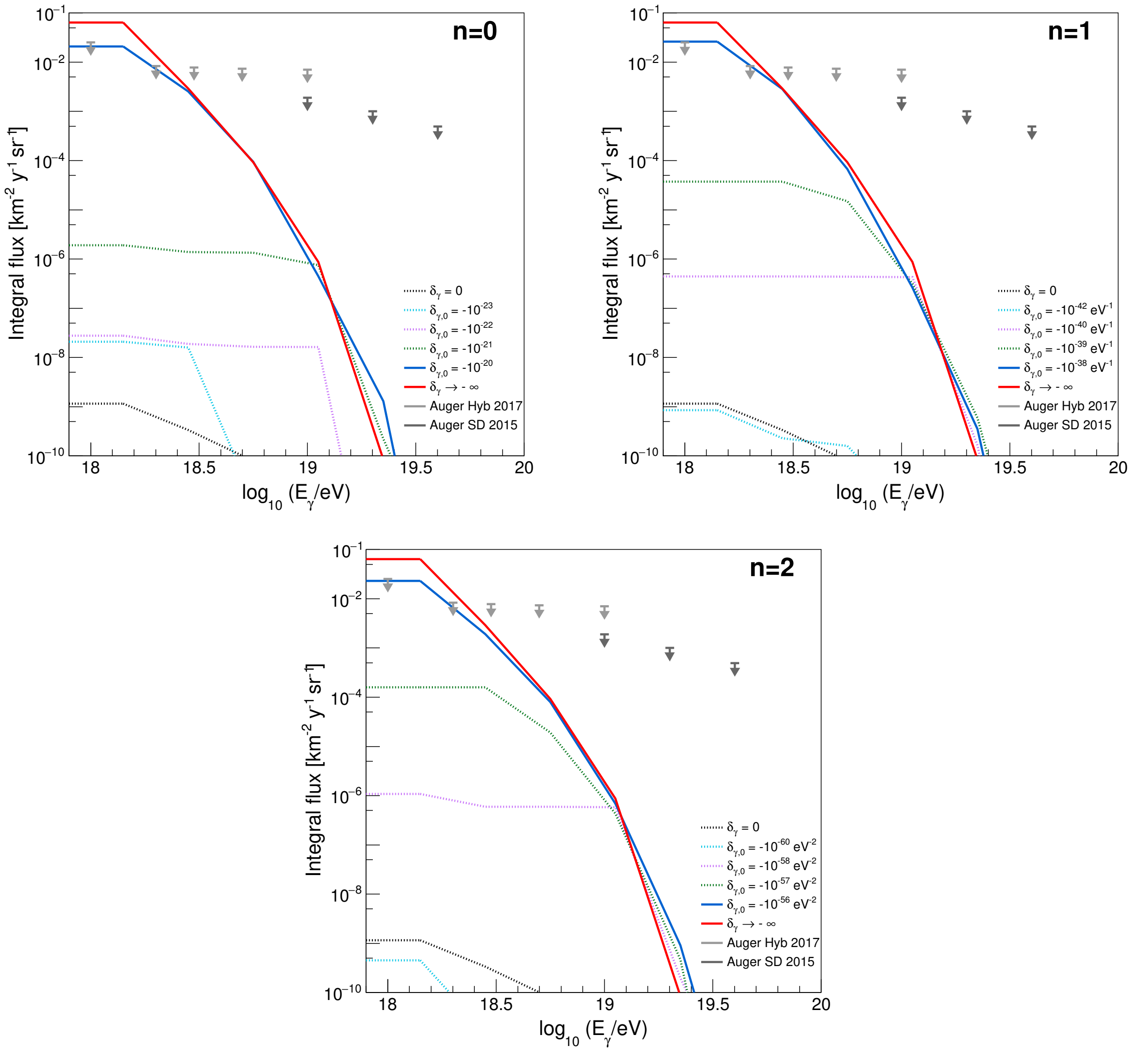

Figure 3: The integral flux of GZK photons as a function of the energy for n =0, 1 and 2 respectively. The black line represents the LI scenario, the red line represents the maximum LIV scenario, and the colored lines represent scenarios with different LIV coefficients. The arrows represent the upper limits from the Pierre Auger Observatory [18]. The dashed lines show scenarios where the predicted flux is weaker than the limits, while the continuous lines show scenarios where the predicted flux is stronger than the limits.

the data available becomes even less sensitive and no conclusion about the LIV models can be assessed for this case.

6. Conclusions

In this contribution, we have discussed the results presented in Ref. [4]. The possibility of probing LIV using UHE astrophysics is examined by considering subluminal LIV effects on the photon sector and changing the propagation of UHE photons. The main effect in the propagation is an increase in the mean free path.

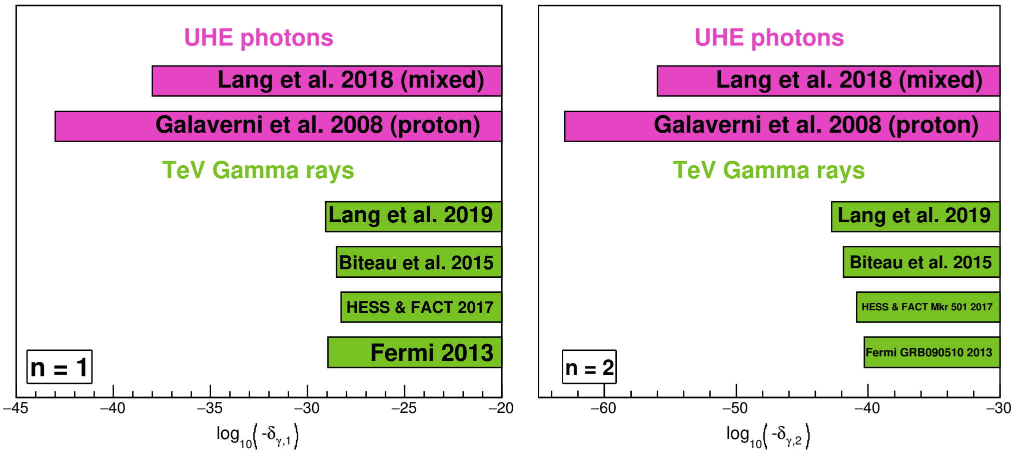

Figure 4: Limits on the LIV coefficient for $n = 1$ and $n = 2$, respectively. In pink, limits obtained using UHE photons [19, 4] and in green limits obtained using TeV gamma-rays [20, 21, 22, 23].

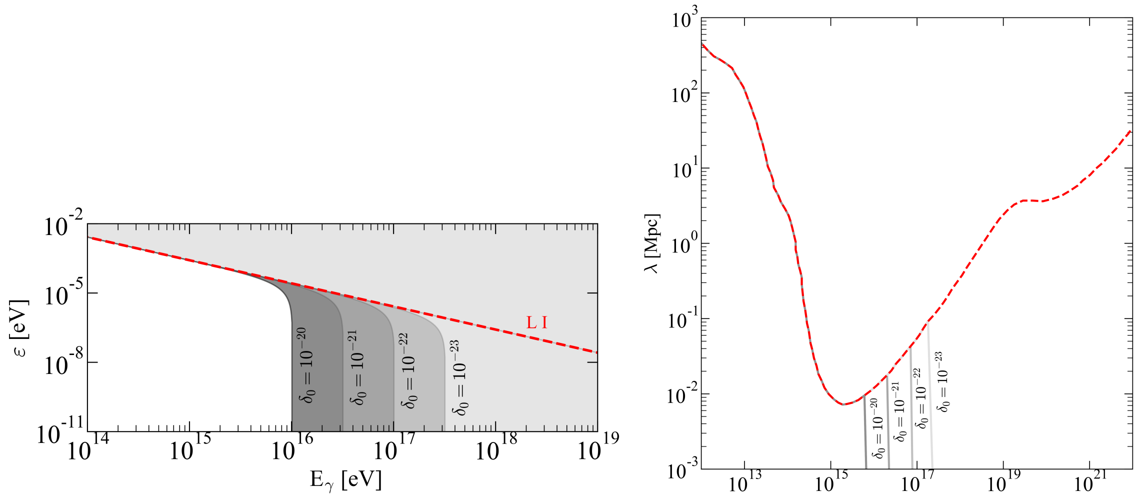

Figure 5: Kinematics of the pair production considering superluminal LIV. The left and right panels show, respectively, the energy threshold and the mean free path as a function of the energy. The red line shows the LI results, while the different shades of gray show the results for several positive LIV coefficients.

The influence of the assumptions about the UHECR in the flux of GZK photons was discussed. A difference of several orders of magnitude is expected for different models and, consequently, it is crucial to be taken into account.

The flux of GZK for different models for the sources of UHECR and LIV scenarios was obtained and compared to upper limits on the photon flux imposed by the Pierre Auger Observatory. In some cases, the expected flux was stronger than the upper limits and, thus, limits on the LIV coefficient were imposed.

For the reference case, limits of the order of $\delta_{\gamma,0} \gtrsim -10^{-20}$, $\delta_{\gamma,1} \gtrsim -10^{-38}$ eV and $\delta_{\gamma,2} \gtrsim -10^{-56}$ eV^2 were imposed. These are several orders of magnitude more restrictive than those imposed with TeV gamma-rays, but the comparison is not straight-forward. The limits presented in this work update previous limits using similar techniques by using more up to date UHECR data.

The effects of superluminal LIV are also discussed. For those, however, the flux of GZK photons decreases and, therefore, using the upper limits on the photon flux to test these superluminal LIV phenomena is not viable in the scope of this work.

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